DOCUMENT RESUME

ED 116 705 IR 002 950

AUTHOR	Collins, Allan
TITLE	Processes in Acquiring Knowledge. Technical Report No. 1.
INSTITUTION	Bolt, Beranek and Newman, Inc., Cambridge, Mass.
SPONS AGENCY	Office of Naval Research, Washington, D.C. Personnel and Training Research Programs Office.
REPORT NO	BBN-R-3231
PUB DATE	Jan 76
NOTE	63p.; To appear in R.C. Anderson, R. J. Spiro, & W.E. Montague, Eds. "Schooling and the Acquisition of Knowledge". Hillsdale, N.J., Erlbaum, 1976
EDRS PRICE	MF-$0.76 HC-$3.32 Plus Postage
DESCRIPTORS	*Computer Assisted Instruction; *Computer Programs; Critical Thinking; *Hypothesis Testing; *Logical Thinking; Programed Tutoring; *Questioning Techniques; Teaching Techniques
IDENTIFIERS	Socratic Teaching

ABSTRACT

A theory of Socratic tutoring was developed in the form of pattern-action rules for a computer program. The rules were derived from analyses of a variety of tutorial dialogs. The 23 rules were designed to formalize causal knowledge and reasoning, and they included such abilities as forming hypotheses, distinguishing between necessary and sufficient conditions, making uncertain predictions, determining the reliability and limitations of these predictions, and asking the right question when there is not enough information to make a prediction. (EMH)

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PROCESSES IN ACQUIRING KNOWLEDGE

Allan Collins

January 1976

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Processes in Acquiring Knowledge

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Bolt Beranek and Newman Inc.
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Contract No. N00014-76-C-0083, effective September 15, 1975.
Expiration Date, September 30, 1976
Total Amount of Contract - $187,000
Principal Investigator, Allan M. Collins [(617) 491-1850)]

Sponsored by:

Office of Naval Research
Contract Authority No. NR 154-379
Scientific Officers: Dr. Marshall Farr and
Dr. Joseph Young

and

Advanced Research Projects Agency
ARPA Order No. 2284, Amendment 5
Program Code No. 61101E

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency, the Office of Naval Research, or the U. S. Government.

To appear in:

R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.) Schooling and the Acquisition of Knowledge. Hillsdale, N. J.: Erlbaum Assoc., 1976.

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This research was sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-76-C-0083, Contract Authority Identification Number, NR 154-379, I would like to thank Marilyn Jager Adams, Nelleke Aiello, John Seely Brown, and Ira Goldstein for valiantly trying to transform the ideas in the paper into a coherent shape.

INTRODUCTION

The purpose of education must always be twofold: to teach a variety of knowledge and to teach the skills necessary for applying that knowledge to new problems or situations. These twin goals are perhaps achieved most successfully through what is usually called the Socratic method of teaching. The Socratic method originated in the Meno dialogue of Plato (1924), but the method has reappeared in different guises throughout history (e.g., the inquiry method, the case method) as it has been applied to different kinds of knowledge. The central notion is to force the student to reason for himself, to derive general principles from specific cases, and to apply the general principles that have been learned to new cases.

In the Socratic method the student learns three kinds of things: (1) specific information about a variety of cases; (2) the causal dependencies or principles that underlie these cases; and (3) a variety of reasoning skills. These include such abilities as forming hypotheses, testing hypotheses, distinguishing between necessary and sufficient conditions, making uncertain predictions, determining the reliability or limitation of these predictions, and asking the right questions when there is not enough information to make a prediction.

The objective of this paper is to define in precise terms what the Socratic method is and how in fact it accomplishes these goals. To this end, I have examined a variety of dialogues involving the Socratic method and tried to formalize the tutoring strategy used in these dialogues as pattern-action rules or production rules (Newell & Simon, 1972), which take the form "If in situation X, do Y". The purpose of writing the rules as productions, is to express the theory in a procedural formalism, that is independent of the particular content. I will also try to specify the reasoning skills that each particular production rule is designed to elicit.

But what is the use of such a theory? The specific use I see is in developing an intelligent CAI system (Brown & Burton, 1975; Collins et al., 1975; Goldstein, Papert & Minsky, in press), that can apply as many of these strategies as possible in tutoring causal knowledge and reasoning. Heretofore the Socratic method has not been considered viable for education generaly, because it is a one-on-one teaching strategy (though R.C. Anderson points out it can be used very successfully in a class). However, the developing technology for building intelligent CAI systems may make it possible to teach many more students with such a tutoring strategy.

More generally the reason for trying to specify the

Socratic method is to move it from the domain of folk wisdom to science. By attempting to formulate the Socratic method as a set of strategies, other theorists have something specific to challenge or revise. Once science has something to chew on, it will inevitably grind the thing into shape.

A THEORY OF SOCRATIC TUTORING

While in one sense the Socratic method is a single approach that involves teaching the student to reason from cases, in another sense it is made up of a variety of specific strategies that good teachers hit upon in the course of their teaching. Some hit upon one set, some upon another, though there is usually some overlap. There is little need for teachers to verbalize these strategies, since their application only depends on an intuitive feel as to how to use them. If they are taught, they are usually taught by example. So there is no very specific body of knowledge about the Socratic method, and hence there is no theory to be extended and refined. In fact until computers provided us with formalisms for expressing "process models," it is unlikely that anyone would have thought of constructing a specific theory about such a thing as the Socratic method.

In order to develop a computational theory of the Socratic method, I have been looking at a variety of

dialogues. These included some dialogues that I conducted myself to teach causal dependencies about geography (Collins et al., 1975), several hypothetical dialogues developed by R.C. Anderson (1972) to illustrate aspects of the Socratic method, and several dialogues produced by the Socratic system developed by Feurzeig (Feurzeig, Munter, Swets, & Breen, 1964; Swets & Feurzeig, 1965). The objective is to extract from these dialogues most of the specific strategies that occur and phrase them as production rules. There is no guarantee of exhaustiveness in this approach, but it should be possible to capture the major strategies.

The production rules are formulated in terms of the functional dependencies in knowledge and general situations that occur in a dialogue. Different rules can often be used in the same situation and sometimes application of one can be delayed until after application of another. Similarly, sometimes one rule is natural follow up to another rule. So what isn't apparent in the enumeration of the rules is the structure of interactions between different rules. This requires a second order theory of teaching strategy that incorporates a notion of what rules are most appropriate to invoke in different situations.

In order to explain the terminology used in the rules that will be presented, it is helpful to consider an example. Figure 1 shows the causal dependencies derived by

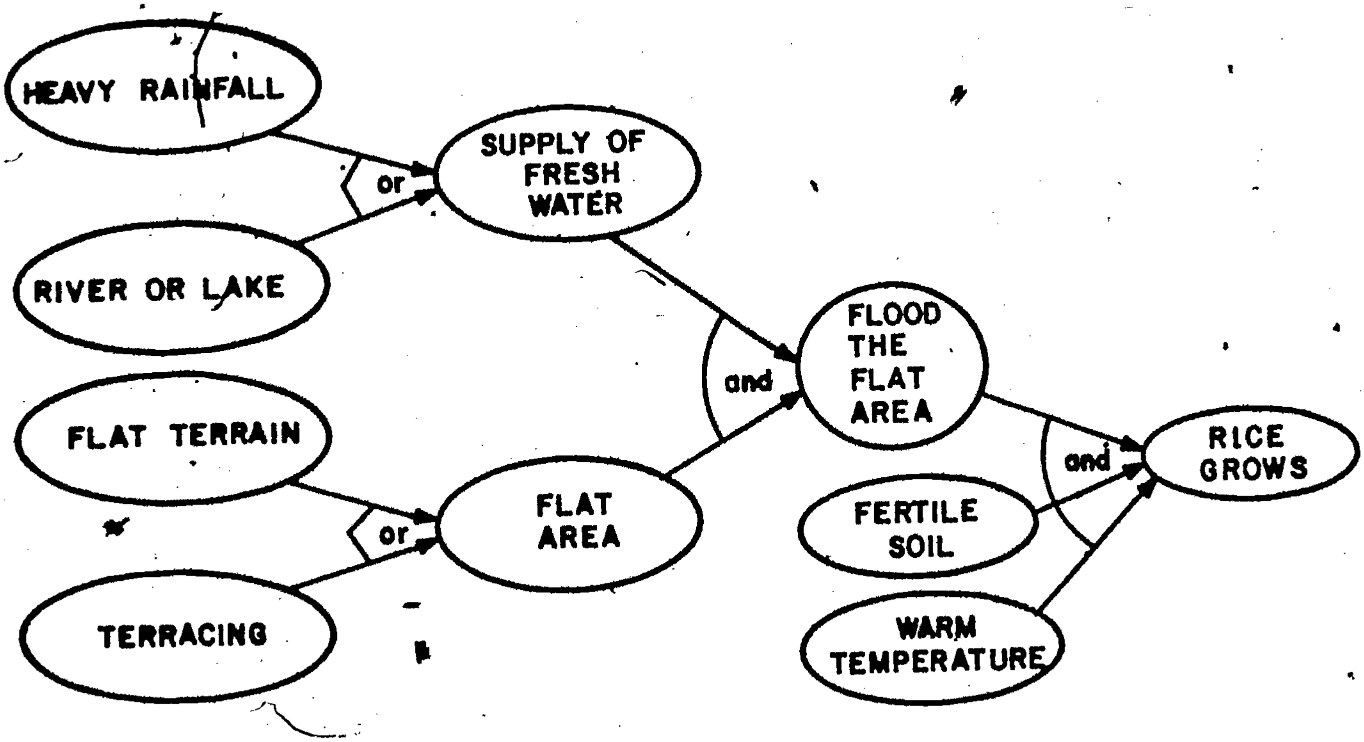

Fig. 1 A student's analysis of the causal factors affecting rice growing.

a student in one of the dialogues that I conducted on rice growing (Collins, et al., 1975). Rice growing is the dependent variable, and in this case it is treated as having two possible values: either you can grow rice or you can't. Unlike rice growing, which the student treated as a threshold function, many dependent variables are treated as continuous functions (e.g. a place is colder or warmer), where there is a continuous range of values.

During the course of the dialogue the student identified four principal factors affecting rice growing: fresh water, a flat area, fertile soil, and warm temperature. These were configured as shown in the diagram. The factors (or functional determinants) such as heavy rainfall or flat terrain are linked to rice growing through chains with various intermediate steps. n fact any node in a chain can be considered as a factor. The diagram itself represents only a top-level description, and any node or link in the diagram can be expanded indefinitely. Causal links expand into intermediate steps, so that for example "irrigation" can be considered an intermediate node on the chain from "river or lake" to "supply of fresh water".

Given the dependencies in the diagram, it is apparent that a factor like heavy rainfall is neither necessary nor

sufficient for rice growing. It is not necessary because obtaining a supply of fresh water (which is a necessary factor) can also be satisfied by irrigation from a river or lake. It is not sufficient because other factors, such as a warm temperature are required. When prior nodes are connected into a node by an "or", any of the prior nodes is sufficient and none is necessary with respect to that node. For example, either heavy rainfall or a river or a lake is a sufficient source for fresh water, but none of these is necessary for fresh water. In contrast, when prior nodes are connected into a node by an "and", all of the prior nodes are necessary and none is sufficient with respect to that node. For example, fresh water is necessary to flood a flat area, but is not sufficient. Though heavy rainfall is sufficient as a source of fresh water, it is not sufficient for growing rice, because of the "ands" in the causal structure between rainfall and rice. By moving down any of the chains, one gets to a higher level of abstraction. But it is not always helpful to know only the most general causes (i.e. the nodes immediately prior to the dependent variable), because the information available about a particular case is often restricted to specific factors further back in the causal structure.

There are different kinds of dependent variables: some vary continuously as do temperature or rainfall, and some vary discretely. For example, different diseases can be

regarded as different values on a single dimension of what's wrong with a patient. Wheat, rice, and corn can be regarded as different values on a dimension of what grain can be grown in a given region. There are several differences between the discrete and continuous cases. First, in the discrete case there may be more or less than one of the values for the dependent variable present (e.g., a patient may have more than one disease or no disease at all), whereas in the continuous case there can only be one value. Second, in the discrete case different causal factors may be relevant for the prediction of different values on the dependent variable (what factors are relevant for predicting mumps may be different from cancer), whereas in the continuous case the same factors are always relevant or irrelevant for making a prediction.

There is a third difference that cuts across the discrete-continuous distinction. In cases such as medical diagnosis or electronic troubleshooting, the causality runs from the dependent variable to the functional determinants (e.g. the disease causes the symptoms), whereas in cases like grain-growing or temperature the causality runs from the functional determinants to the dependent variable. In the case of identifying a letter from its features there is no causality in either direction, but still different letters can be treated as values of the dependent variable and the features as different factors. Despite these

differences in the domains of knowledge studied, it turns out the tutoring strategies can be characterized in a single framework.

I have listed below the rules (or important strategies) derived so far, as well as brief explanations of why they are effective strategies. Examples of each are given in terms of the causal factors for average temperature or for growing rice. More examples will occur in the following section where the rules are illustrated by some of the actual dialogues from which they were derived.

RULE 1: <u>Ask about a known case</u>

If 1) it is the start of a dialogue, or

2) there is no other strategy to invoke,

then 3) pick a well-known case and ask what the value of the dependent variable is for that case, or

4) ask the student if he knows a case with a particular value on the dependent variable.

EXAMPLE:

Ask the student "Do they grow rice in China?" or "Do you know any place where rice is grown?"

REASON FOR USE:

It brings out any well-known cases the student knows about such as rice growing in China.

RULE 2: <u>Ask for any factors</u>

If 1) a student asserts that a case has a particular value on the dependent variable,

then 2) ask the student why.

EXAMPLE:

If a student says they grow rice in China, ask why.

REASON FOR USE:

This determines what causal factors or chains the student knows about.

RULE 3: <u>Ask for intermediate factors</u>

If 1) the student gives as an explanation a factor that is not an immediate cause in the causal chain,

then 2) ask for the intermediate steps.

EXAMPLE:

If the student mentions monsoons in China, as a reason for rice growing, ask "Why do monsoons make it possible to grow rice in China?"

REASON FOR USE:

This insures that the student understands the steps in the causal chain, for example that rice needs to be flooded.

RULE 4: <u>Ask for prior factors</u>

If 1) the student gives as an explanation a factor on causal chain where there are also prior factors,

then 2) ask the student for the prior factors.

EXAMPLE:

If the student mentions water as a factor in growing rice, ask him "What do you need to get enough water?"

REASON FOR USE:

Same as RULE 3.

RULE 5: Form a general rule for an insufficient factor

If 1) the student gives as an explanation one or more factors that are not sufficient,

then 2) formulate a general rule asserting that the factor given is sufficient and ask the student if the rule is true.

EXAMPLE:

If the student gives water as the reason they grow rice in China, ask him "Do you think any place with enough water can grow rice?"

REASON FOR USE:

This forces the student to pay attention to other causal factors.

RULE 6: Pick a counterexample for an insufficient factor

If 1) the student gives as an explanation one or more factors that are not sufficient, or

2) agrees to the general rule in RULE 5,

then 3) pick a counterexample that has the right value on the factor(s) given, but

the wrong value on the dependent variable, and

4) ask what the value of the dependent variable is for that case, or

5) ask why the causal dependence does not hold for that case.

EXAMPLE:

If a student gives water as the reason they grow rice in China or agrees that any place with enough water can grow rice, pick a place like Ireland where there is enough water and ask "Do they grow rice in Ireland?" or "Why don't they grow rice in Ireland?"

REASON FOR USE:

Same as RULE 5.

RULE 7: <u>Form a general rule for an unnecessary factor</u>

If 1) the student gives as an explanation one or more factors that are not necessary,

then 2) formulate a general rule by asserting that the the factor is necessary and ask the student if the rule is true.

EXAMPLE:

If a student says rainfall is a reason for growing rice, ask "Do you think it is necessary to have heavy rainfall in order to grow rice?"

REASON FOR USE:

This forces the student to consider the necessity of a

particular factor.

RULE 8: Pick a counterexample for an unnecessary factor

If 1) the student gives as an explanation one or more factors that are not necessary, or

2) the student agrees to the general rule in RULE 7,

then 3) pick a counterexample with the wrong value on the factor and the correct value on the dependent variable, and

4) ask the student what the dependent value is for that case, or

5) ask why the causal dependence doesn't hold in that case.

EXAMPLE:

If the student gives rainfall as a reason for growing rice, ask "Do you think they can grow rice in Egypt?" or "Why do they grow rice in Egypt when they don't have much rainfall?"

REASON FOR USE:

Same as Rule 7.

RULE 9: Pick a case with an extreme wrong value

If 1) the student is missing a particular factor,

then 2) pick a case with an extreme wrong value on that factor and ask why not there.

EXAMPLE:

If the student has not mentioned temperature with respect to rice growing, ask "Why don't they grow rice in Alaska?"

REASON FOR USE:

This forces the student to pay attention to any factor he is ignoring.

RULE 10: Pose a misleading question

If 1) there is a case where a secondary factor overrides the primary factors,

then 2) pose a misleading question to the student, based on the fact that the value of the dependent variable is different from what would be predicted from the primary factors above,

or

3) pose a misleading choice as to the dependent variable between two cases where consideration of the primary factors alone leads to the wrong prediction.

EXAMPLE:

Because the tree cover in the Amazon jungle keeps the temperature down to a high of about 85 degrees, ask the student "Do you think the temperatures in the Amazon jungle reach a 100 degrees?" or "Do you think it gets hotter in the Amazon jungle or Texas?"

REASON FOR USE:

This forces the student to learn about common exceptions,

about secondary factors, and about the limitations of general rules.

RULE 11: <u>Specify how the variable depends on a given factor</u>

If 1) the student mentions a factor, but does not specify how the dependent variable varies with that factor, or

2) only partially specifies the relationship,

then 3) ask him to specify the relationship more precisely, or

4) suggest a possible relationship to him.

EXAMPLE:

Ask the student "Can you say how temperature depends on latitude?" or "Does average temperature increase linearly the further south you go?"

REASON FOR USE:

This forces the student to specify more precisely the functional relation between the factor in question and the dependent variable.

RULE 12: <u>Probe for a necessary factor</u>

If 1) a student makes a wrong prediction on the dependent variable because he has not identified one or more necessary factors,

then 2) tell him he is wrong, and ask him to think of another factor that is necessary.

EXAMPLE:

If a student thinks they can grow rice in Ireland because it's wet, point out they can't grow rice there and ask "Can you make a hypothesis about what other factor is necessary for rice growing?"

REASON FOR USE:

This forces the student to use hypothesis formation as a systematic strategy for dealing with unexplained problems.

RULE 13: Probe for a sufficient factor

If 1) a student makes a wrong prediction on the dependent variable because he treats a factor as necessary when it is not,

then 2) tell him he is wrong, and ask him to formulate a hypothesis about another factor that might be sufficient.

EXAMPLE:

If a student thinks they cannot grow rice in Egypt because there is little rain, point out they can grow rice there and ask "Can you think of what other factor makes it possible to grow rice there?"

REASON FOR USE:

Same as RULE 12.

RULE 14: Probe for differences between two cases

If 1) a student cannot think of a factor that could

account for different values of the dependent variable between two cases,

then 2) ask him to consider what the differences are between the two cases that might account for the difference in the dependent variable.

EXAMPLE:

If a student cannot think of why they can grow rice in China but not in Alaska, ask what the differences are between China and Alaska that might account for the difference in rice growing.

REASON FOR USE:

Same as RULE 12.

RULE 15: <u>Request a test of the hypothesis about a factor</u>

If 1) the student has formulated a hypothesis, about how the dependent variable is related to a particular factor,

then 2) ask him how it could be tested.

EXAMPLE:

Ask the student "If you want to test whether distance from the ocean affects temperature, would you compare the temperature in January for St. Louis to Washington, D.C. or Atlanta?"

REASON FOR USE:

By getting the student to test hypotheses, it forces him to learn how to control other factors that might affect the variable.

RULE 16: Ask for a prediction about an unknown case

If 1) a student has identified all the primary factors that affect the dependent variable,

then 2) pick a case that is either hypothetical or unlikely to be known and ask the student to predict the likely value on the variable for that case.

EXAMPLE:

If the student has identified the factors that affect rice growing, then ask "Do you think they can grow rice in Florida?"

REASON FOR USE:

This forces the student to use the factors he has accumulated in a predictive way.

RULE 17: Ask what are the relevant factors to consider

If 1) the student can't make a prediction,

then 2) ask the student what are the relevant factors to consider.

EXAMPLE:

Ask the student "If you can't predict whether they grow rice in Florida, what factors do you need to consider?"

REASON FOR USE:

This teaches the student to ask the right questions in trying to make reasonable predictions about new cases.

RULE 18: Question prediction made without enough information

If 1) a student makes a prediction as to the value of the dependent variable on the basis of some set of factors, and

2) there is another value consistent with that set of factors,

then 3) ask the student why not the other value.

EXAMPLE:

If the student predicts they grow wheat in Nigeria because it is fertile and warm, ask him why not rice.

REASON FOR USE:

This forces the student not to jump to conclusions without enough information.

RULE 19: Point out irrelevant factors

If 1) the student asks about the value of an irrelevant factor in trying to make a prediction,

then 2) point out the factor is irrelevant, or

3) ask whether the irrelevant factor affects the dependent variable.

EXAMPLE:

If the student asks whether Denver or Salt Lake City is further west in trying to decide which has the colder temperature, then point out that longitude doesn't matter, or ask whether longitude affects temperature,

REASON FOR USE:

This forces the student to learn what is irrelevant, as

well as what is relevant, in making any decision.

RULE 20: Point out inconsistent prediction

If 1) a student makes a prediction about the dependent variable inconsistent with any of the values of the factors discussed,

then 2) point out the inconsistency, or

3) ask whether the value of the factor discussed is consistent with his prediction about the dependent variable.

EXAMPLE:

If the student predicts they grow rice in Spain after the dryness of the climate has been discussed, either point out that a dry climate is incompatible with rice unless there is irrigation, or ask how he thinks they can grow rice when the climate is so dry.

REASON FOR USE:

This reminds the student to consider all the relevant factors in making a prediction, and insures he understands the relation between the factor and the dependent variable.

RULE 21: Ask for consideration of a possible value

If 1) there is a value on the dependent variable that has not been considered and which either is consistent with several factors or important to consider a priori,

then 2) ask the student to consider that value.

EXAMPLE:

If the student hasn't considered rice as a possible grain in Nigeria, ask him to consider it.

REASON FOR USE:

This forces the student to actively consider alternatives in making any prediction.

RULE 22: <u>Test for consistency with a given hypothesis</u>

If 1) a particular value on the dependent variable is being considered, and

2) the values of one of more relevant factors have been discussed, but

3) whether these values are consistent with the particular value of the dependent variable has not been discussed,

then 4) pick one or more of the factors that are consistent with the dependent variable and ask if they are consistent, or

5) pick one or more of the factors that are inconsistent with the dependent variable and ask if they are consistent.

EXAMPLE:

If the hot climate and rainfall in Java has been discussed, the student can be asked "Is the heavy rainfall in Java consistent with growing wheat?" or "IS the hot climate and heavy rainfall

consistent with growing rice?"

REASON FOR USE:

This tests whether the student understands the functional relations between the various factors and the dependent variable.

RULE 23: Ask for consideration of relevant factors

If 1) a student makes a wrong prediction in a particular case, or

2) cannot make a prediction,

then 3) pick the most relevant factor not discussed and

4) ask student what the value of that factor is for the particular case.

EXAMPLE:

If the student predicts that the average temperature is very hot in Buenos Aires, ask if he knows what the latitude of Buenos Aires is.

REASON FOR USE:

This forces the student to consider relevant factors in making a prediction, and elicits whether a mistake is due to wrong information about a case, or a mistake about how the dependent variable varies with different factors.

DATA ON WHICH THE THEORY IS BASED

In this section I have included segments of some of the dialogues I have been looking at in order to specify the various tutoring strategies used in the Socratic method. Each rule from the previous section that is used in one of the dialogues is indicated in parentheses. Often the tutor is not applying one of the tutoring strategies but answering a student's question or further specifying a question. Sometimes, however, he may be applying a strategy that has not yet been incorporated into the theory, through ignorance or oversight.

Tables 1 and 2 show fragments of two of the dialogues I conducted to teach different causal interdependencies in geography (Collins et. al., 1975). These dialogues show heavy use of the counterexample strategies (Rules 6 & 8) and the strategies directed towards getting the student to make predictions using the factors he accumulated. The student appeared to be learning a great deal in these dialogues as is detailed in Collins, et al.

Table 1 includes fragments from a dialogue about grain-growing (in particular, rice, wheat, and corn) conducted with a rather sophisticated student. The

Table 1

Fragments of a dialogue on growing grain (Collins et al., 1975)

1 T: Where in North America do you think rice might be grown? (Rule 1: Ask about a known case)

2 S: Louisiana.

3 T: Why there? (Rule 2: Ask for any factors)

4 S: Places where there is a lot of water. I think rice requires the ability to selectively flood fields...

5 T: O.K. Do you think there's a lot of rice in, say, Washington and Oregon? (Rule 6: Pick a counterexample for an insufficient factor)

6 S: Aha, I don't think so.

7 T: Why? (Rule 2: Ask for any factors)

8 S: There's a lot of water up there too, but there's two reasons. First the climate isn't conducive, and second, I don't think the land is flat enough. You've got to have flat land so you can flood a lot of it, unless you terrace it.

9 T: What about Japan? (Rule 8: Pick a counterexample for an unnecessary factor)

10 S: Yeah, well they have this elaborate technology I suppose for terracing land so they can flood it selectively even though its tilted overall.

(section omitted)

11 T: Do you think they might grow rice in Florida? (Rule 16: Ask for a prediction about an unknown case)

12 S: Yeah, I guess they could, if there were an adequate fresh water supply. Certainly a nice, big, flat area.

(section omitted)

13 T: What kind of grains do you think they grow in Africa, and where, then? (Pause) Well, where would they grow rice if they grew it anywhere? (Rule 16 again)

14 S: If they grew it anywhere, I suppose they'd grow it in the Nile region, and they'd grow it in the tropics where there was an adequate terrain for it.

(section omitted)

15 T: What do you think they live on (in West Africa)? (Rule 16 again).

16 S: I guess they grow some kind of grain in West Africa.

17 T: What kind is most likely?

18 S: Wheat.

19 T: You think wheat is the most likely grain?

20 S: Wheat or some combination of wheat and rice if they can grow it, and I suppose they could. I don't really know much about the geography there, but I suppose there are places, like Nigeria is pretty damn fertile.

21 T: O.K. its fertile but what other qualities? Is the temperature warm or cold? (Rule 23: Ask for consideration of different factors)

22 S: Yeah, the climate's temperate and...

23 T: Do they have rain or not? (Rule 23 again)

24 S: Yeah.

25 T: They have a lot of rain. O.K. What do those kind of configurations predict as far as grain? (Rule 16 again)

26 S: Rice.

beginning section of Table 1 (lines 1-10) illustrates the use of both counterexample strategies. In one case (line 5) the tutor chose Washington and Oregon because they have a lot of water but no rice; in the other case (line 9) he chose Japan because it is mountainous, but has rice. In the first case enough water was not sufficient for growing rice; in the second case flat land was not necessary for growing rice.

The next three segments of Table 1 show the tutor asking for predictions about unknown cases (lines 11, 13 and 15) after the student had developed the structure of causality about rice-growing depicted in Fig. 1. In the last case the student incorrectly predicted that wheat is grown in Nigeria, so the tutor asked him to consider the relevant factors one by one. After doing this the student changed his prediction to rice, which was correct.

Table 2 shows the middle of a dialogue on population density with a less sophisticated student than the one above. To get this student to think about the relevant factors, it was often necessary to use a strategy of picking a case which nas an extreme wrong value on one of the factors that affects the dependent variable (i.e.

Table 2

Fragments from the middle of a dialogue on population density (Collins et al, 1975).

1 T: In Northern Africa is there a large population density there? (Rule 9: Pick a case with an extreme wrong value)

2 S: In Northern Africa? I think there is.

3 T: Well there is in the Nile valley, but elsewhere there is not. Do you have any idea why not? (Rule 12: Probe for a necessary factor)

4 S: Because its not good for cultivating purposes?

5 T: Its not good for agriculture?

6 S: Yeah.

7 T: And do you know why? (Rule 4: Ask for prior factors)

8 S: Why?

9 T: Why is the farming at a disadvantage?

10 S: Because its dry.

11 T: Right.

(section omitted)

12 T: Do you know why there is sparse population in Tibet now? (Rule 9 again)

13 S: Because its desert?

14 T: No.

15 S: No? I don't know. Oh you said it was mountainous.

16 T: Very mountainous.

17 S: So it isn't good farmland.

18 T: OK. It's very tough to farm when you have mountains there. You only have valleys to farm in. O.K. Now do you think its very dense in Alaska? (Rule 9 again)

19 S: No.

20 T: Why? (Rule 2: Ask for any factors)

21 S: I would imagine because of the cold.

22 T: The cold climate. And why does a cold climate...? (Rule 3: Ask for intermediate factors)

23 S: There again you would have the problem of farming and agriculture.

24 T: O.K. And are there possibly other reasons why a cold climate leads to low density? (Rule 3 again)

25 S: Yeah. You would use up more heat and fuel. They wouldn't think of it as a desirable place to locate.

population density). Thus, northern Africa (line 1) was chosen to elicit discussion about water, Tibet (line 12) to elicit discussion about mountains, and Alaska (line 18) to elicit discussion about cold climate. The extreme value in each case forced the student to pay attention to a relevant factor she was ignoring.

In the discussion about Alaska, the tutor's probing for various intermediate and prior factors led the student to construct a somewhat complex network of causal interconnections. In particular, the student suggested that cold climate leads to low population density by three causal chains: one through agricultural problems, one through fuel needs, and one through people's desire not to settle in cold climates. Earlier two other factors, dryness and mountains, had been causally linked to agricultural problems. This illustrates the complex interconnections that can occur among causal chains.

Table 3 is a hypothetical dialogue developed by Anderson (1972) to illustrate the power of the Socratic method as a teaching strategy. What is most important about the teaching strategies in this dialogue is the way they force the student to use hypothesis formation and testing as systematic strategies for reasoning about causal dependencies.

Table 3

A hypothetical dialogue by R.C. Anderson (1972)

1 T. Which is likely to have the coldest winter days, Newfoundland or Montana? (Rule 10: Pose a misleading choice where a secondary factor overrides the primary factor)

2 S. Newfoundland.

3 T. Please give your reasons for answering Newfoundland. (Rule 2: Ask for any factors)

4 S. Newfoundland is further north.

5 T. Yes, Newfoundland is further north than Montana. Are you arguing, then, that if you take any two places in the Northern Hemisphere, the one which is further north will have the lower average winter temperature? (Rule 5: Formulate a general rule for an insufficient factor)

6 S. Yes, I guess so.

7 T. I'll tell you now that Montana has lower average winter temperatures than Newfoundland. Does this fact

cause you to change your reasoning? (Rule 12: Ask for another necessary factor)

8 S. Yes.

9 T. In what way?

10 S. Being further north isn't as important as I thought.

11 T. Please try to be more precise. Would you, for instance, say that if you take any two places in the Northern Hemisphere, the one furthest south has the colder winter temperatures? (Rule 11: Specify the relationship between a factor and the variable)

12 S. No, I wouldn't say that.

13 T. What would you say? (Rule 11 again)

14 S. I'm not sure.

15 T. Would you say that how far north a place is has no effect on temperature? (Rule 11 again)

16 S. No, I know it has some effect.

17 T. Yes, you're right. Distance north does affect temperature, so what do you conclude? (Rule 12 again)

18 S. I don't understand the question.

19 T. You know that how far north a place is situated, is one factor that affects the temperature. Yet, you also know that, even though it is further north, Newfoundland has higher average winter temperatures than Montana. What must this mean? (Rule 12 again)

20 S. Some other factor besides north-south distance must also affect temperature.

21 T. Yes! Right! What could this factor be?

22 S. I don't have any idea.

23 T. Why don't you look at your map of North America. Do you see any differences between Montana and Newfoundland? (Rule 14: Ask for differences between two cases)

24 S. Montana is in the centre of the country. Newfoundland is on the ocean.

25 T. What do you mean by "in the centre of the country?"

26 S. It's a long way from the ocean.

27 T. Do you suppose that distance from the ocean affects temperature?

28 S. I'm not sure. It would just be a guess.

29 T. True! The name for such a guess is hypothesis. Supposing the hypothesis were correct, what exactly would you predict? (Rule 11 again)

30 S. The further a place is from the ocean, the lower the temperature will be in the winter.

31 T. How could you test your hypothesis? (Rule 15: Ask for a test of hypothesis about a factor)

32 S. By comparing temperatures of places different distances from the ocean.

33 T. Very good. Let's do that. Suppose we take St. Louis, Missouri. Which would be best to compare, Atlanta, Georgia, or Washington, D.C.....? (Rule 15 again)

34 S. I'm not sure.

35 T. Why don't you look at your map? Maybe that will help you decide.

36 S. I would pick Washington.

37 T. Why?

38 S. Because it's at the same latitude as St. Louis.

39 T. Why is that important?

40 S. Well, if Atlanta were warmer, I wouldn't know whether it was because it was nearer the ocean or further south.

41 T. Good thinking.

In Table 3 the initial question by the tutor was designed to entrap the student into saying that Newfoundland is colder than Montana, because its latitude is further north, when in fact Newfoundland is warmer, because of the ocean. A similar kind of entrapment occurred in one of my dialogues, where the question was designed to elicit a wrong prediction about the value of the dependent variable:

(T) Is it very hot along the coast here? (points to Peruvian Coast near the equator) (Rule 10: Pose a misleading question where a secondary factor overrides the primary factor.)

(S) I don't remember.

(T) No. It turns out there's a very cold current coming up along the coast; and it bumps against Peru, and tends to make the coastal area cooler, although it's near the equator.

Like the counterexample and extreme value strategies this strategy involves the careful selection of cases to bring up certain factors.

In line 5 the tutor formulated a general rule, which was incorrect, by suggesting that the insufficient factor (latitude) mentioned by the student was sufficient to determine the dependent variable temperature (Rule 5). This strategy is an alternative to selecting a counterexample by

Rule 6 ("London is further north than New York and yet it's warmer") or telling the student he is wrong and asking for another factor that affects temperature (Rule 12). Though it did not occur in any of the dialogues, there must also be the possibility of formulating a general rule (Rule 7) by asserting that an unnecessary factor the student mentions is necessary.

When the student agreed to the general rule, the tutor pointed out the error (line 7) and started a series of questions designed to force the student to figure out that distance from the ocean affects temperature. By applying Rule 12 in line 7 and again in lines 17 and 19, the tutor tried to get the student to hypothesize another factor that might account for his error in prediction. In lines 11, 13, and 15 he tried to test the student's understanding of the relation between latitude and temperature (Rule 11). Finally, in line 23 he asked the student to consider what differences between the two cases might account for the effect on the dependent variable (Rule 14), and this succeeded in eliciting distance from the ocean.

The tutor then tried to get the student to test the hypothesis he had formulated; first by asking a very general question (line 31), and then a quite specific question (line 33). In lines 35, 37, and 39 the tutor appears to be using variations of several of the rules (Rules 14, 2, and 4

respectively) with a dependent variable something like "good vs. bad comparison in order to test the effect of distance from the ocean," but it is not clear to me how to fit the rules above, or any other rules, to the three questions. This failure suggests that the rules as presently formulated are too close to the surface structure of the dialogue.

The hypothetical dialogue by R.C. Anderson in Table 4 illustrates the use of the Socratic strategy for tutoring moral causation. It shows an extended use of two similar cases to elicit causal factors that can account for the student's assertion that the cases differ on the dependent variable (i.e. whether the rebels should be admired or not). A similar extended comparison of two cases occurred in a dialogue on population density (Collins et al., 1975) where the comparison was between Java with high density and other Indonesian islands with low density. Comparison of cases is intrinsic to the Socratic strategy, and similar cases that have different values on the dependent variable usually require the most extensive elaboration of the underlying causal structure to explain.

Figure 2 shows the causal structure that was derived by the student during the dialogue. I have depicted it here to

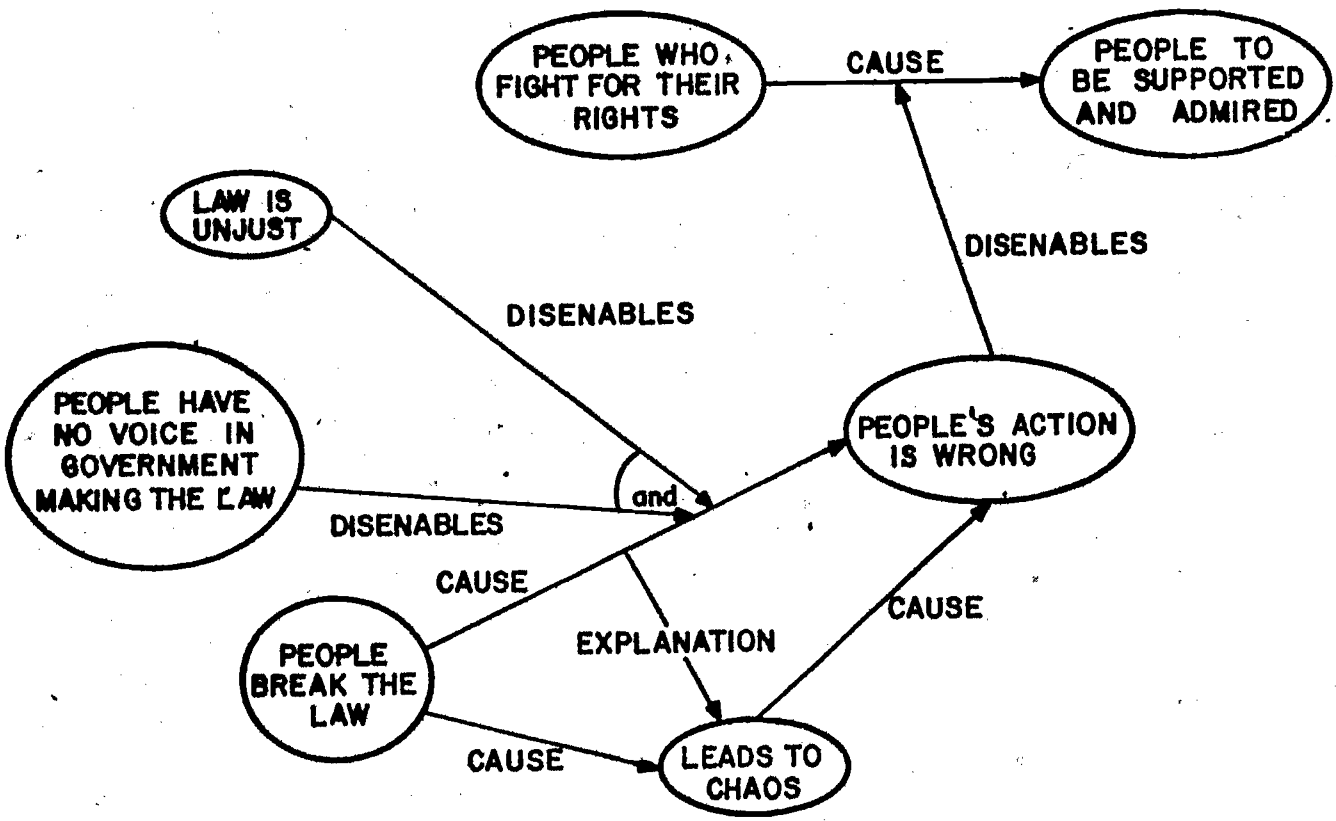

Fig. 2 The causal structure built up by the student during the dialogue in Table 4.

help explain how the Socratic rules were applied in this dialogue fragment. There are two aspects of the diagram that differ from Fig. 1: the explanation link and the disenabling link, both of which relate causal links to other nodes. In a more detailed representation these two kinds of links would be attached to causal nodes with antecedent and consequent links (see Norman, Rumelhart, & the LNR research group, 1975). The explanation link is a formalism to allow for expansion of any causal link into its intermediate steps, which the student was forced to do by one of the teacher's questions. The notion of disenablement derives from Abelson (1973), and was necessary to characterize the way the student treated certain concepts as negating other causal dependencies.

The dialogue starts with the teacher picking a well known case, the American revolution, and asking for the value of the dependent variable "which side to support." The student said he would support the American side, because they fought for their rights. This established the first causal dependency in Fig. 2. In line 5, as in the earlier dialogue, the tutor formulated the student's explanation as a general rule, altering slightly the dependent variable from "support" to "admire". Again the student agreed with

Table 4

A hypothetical dialogue by R.C. Anderson (1972)

1 T: If you'd been alive during the American Revolution, which side would you have been on? (Rule 1: Ask about the value of the dependent variable for a known case)

2 S: The American side

3 T: Why? (Rule 2: Ask for any factors)

4 S: They were fighting for their rights.

5 T: You admire people who fight for their rights. Is that true? (Rule 5: Formulate a general rule for an insufficient factor)

6 S: Yes.

7 T: How about the young men who broke into the draft office and burned the records? Do you admire them? (Rule 6: Pick a counterexample to the general rule)

8 S: No, what they did was wrong.

9 T: I thought you said you admired people who fight for

their rights; so why don't you admire the draft resistors? (Rule 21: Ask for consideration of a possible value)

10 S: I do admire them in a certain sense, but what they did was wrong.

11 T: What was wrong about it? (Rule 4: Ask for prior factors)

12 S: They broke the law.

13 T: Why is that wrong? (Rule 3: Ask for intermediate factors)

14 S: It's obvious. If everyone broke the law there would be chaos.

15 T: You are saying that what the draft resistors did was wrong because they broke the law. The American revolutionaries broke the laws, too. Therefore, to be consistent, you would have to say that what they did was wrong. (Rule 6: Pick a counterexample for an insufficient factor)

16 S: That was different. Those were unjust laws. They

didn't recognize the authority of the government of that time.

17 T: The draft resistors say that the war in Viet Nam is immoral. They say that they have the right, in fact a moral obligation, to defy the laws that support this war. (Rule 6 again).

18 S: I don't think Viet Nam is such a good thing, but you just can't have individuals deciding which laws they are going to obey.

19 T: So, you would say the American revolutionaries should have followed the law. (Rule 20: Trace the consequences of an inconsistent prediction)

20 S: Yes, I guess so.

21 T: If they had obediently followed all the laws we might not have had the American Revolution. Is that right? (Rule 20 again)

22 S: Yes.

23 T: They should have obeyed the laws even if they believed they were unjust. Is that right? (Rule 20 again)

24 S: I'm not sure. I suppose I have to say yes.

25 T: In other words what the American revolutionaries did was wrong. That's true isn't it? (Rule 20 again)

26 S: No, damn it. They were in the right. They were fighting for their liberty. They didn't have any voice in the government. There was taxation without representation.

27 T: So you would say that people do have a right to disobey laws if they don't have a voice in the government? (Rule 5: Formulate a general rule for an insufficient factor)

28 S: Yes

29 T: The draft resistors don't have a voice in the government. According to what you have said, this means they do have a right to disobey the draft laws. Is that true? (Rule 6 again)

30 S: No. We have a democracy. The President and Congress are elected by the people. Therefore, the draft resistors are represented. They do have a voice.

the general principle, but instead of telling the student he was wrong, the tutor responded with a counterexample. He chose as a counterexample a group of people the student was not likely to admire, but who were fighting for their rights. In order to deal with this counterexample the student declared that the causal dependency above was disenabled when the people's actions were wrong. This established the first disenablement in Fig. 2.

The tutor further elaborated the student's causal structure by several "why" questions that established the notion that breaking the law leads to actions being wrong. Then the tutor in line 15 brought up the American revolutionaries as a counterexample, because they too broke the law, though the student did not regard their actions as wrong. To deal with this counterexample, the student developed the disenablement that unjust laws are all right to break. Then the tutor in line 17 returned again to the draft resistors as a counterexample, because they too broke what they considered to be unjust laws. At this point the student temporarily gave up the disenablement he had proposed. But in tracing the consequences of the causal structure built up (lines 19-25), he realized that another disenabling condition ("the people having no voice in the government" together with "unjust laws") will differentiate the American revolutionaries from draft resistors. Thus the dialogue ended with a partial victory by the student and the

development of a complicated causal structure.

Tables 5 and 6 show two short dialogues with the Socratic system (Swets & Feurzeig, 1965): in the first the student tries to identify the disease of a patient given various symptoms and in the second he tries to identify a random letter of the alphabet given various features. This was a CAI system developed to force the student to reason with causal dependencies he had already learned, such as goes on in medical diagnosis. This system is particularly rich in strategies for dealing with predictions by the student, and, in particular, forcing him to consider relevant factors, to ignore irrelevant factors, and to consider alternative hypotheses.

Table 5 is from the middle of a dialogue where the student had earlier collected a large amount of data about the particular case. The fragment starts out by testing the student's ability to make a prediction about the dependent variable for this case, where the correct solution is unknown. There are two rather nice strategies that occurred after this. One strategy (line 9) involved asking the student to consider a hypothesis about the dependent variable other than the one generated by the student

Table 5

Dialogue with the Socratic System on medical diagnosis.

(Swets & Feurzeig, 1965)

1 T: We've got a fair amount of information -- at least enough to raise some, perhaps several, diagnostic possibilities. Have you any in mind? (Rule 16: Ask for a prediction about an unknown case)

2 S: Yes.

3 T: Name one.

4 S: Pulmonary infarction.

5 T: Fine. Pleural pain, dyspnea, fever and the physical exam signs and symptoms are certainly consistent with pulmonary infarction. Do you think that shaking chills and the presence of rusty sputum further support this diagnosis? (Rule 22: Test for consistency with a given hypothesis)

6 S: No.

7 T: Right. Though the white count is consistent, isn't it? (Rule 22 again)

8 S: No.

9 T: Wrong. The white count is consistent. This should further support your diagnosis. We've considered one possibility. Do you have another diagnosis in mind? (Rule 16 again)

10 S: No.

11 T: In that case I'd like to talk about viral pneumonia. (Rule 21: Ask for consideration of a possible value). The tachycardia, high WBC, elevated respiratory rate, shaking chills, bloody sputum, and severe pleural pain all lend weight to that diagnosis -- right? (Rule 22: Test for inconsistency with a given hypothesis)

12 S: Yes

13 T: You're way off base. There's not an iota of truth to any part of what I just said; in fact, the opposite of what I said is true. You'd better review some elementary medicine, doctor.

himself. The other strategy (lines 5, 7, and 11) involved asking the student to consider whether various symptoms (or factors) were consistent with the value of the dependent variable being considered. Both of these strategies tested the student's knowledge of how different factors relate to different values of the dependent variable.

In Table 6 three other strategies occurred which teach important reasoning skills. One strategy (lines 9 and 11) questions any predictions that are made without enough information. Another strategy (line 13) questions the student if he asks about information that is irrelevant to predicting the value of the dependent variable. The third strategy (line 17) points out when a prediction is inconsistent with the factors that have been discussed. These three strategies stress the skills of asking the right questions and not jumping to a conclusion too quickly.

CONCLUSIONS

The theory has taken the particular shape it currently has because of the particular dialogues that were available to me for analysis. There is a need to look at a wider range of dialogues, such as the Meno itself, in order to obtain a more complete set of rules. Furthermore, because I

Table 6

A dialogue with the Socratic System to identify a letter
(Swets & Feurzeig, 1965)

1 T: Start when ready.

2 S: CURVES?

3 T: One.

4 S: LOOSE ENDS?

5 T: Two.

6 S: OBLIQUES?

7 T: Zero.

8 S: C.

9 T: You don't have enough information yet to get the right answer. How do you know it isn't J, for example? (Rule 18: Question a prediction made without enough information)

10 S: J.

11 T: You don't have enough information yet. How do you know it isn't C, for example? (Rule 18 again)

12 S: HORIZONTALS?

13 T: Zero. That was a wasted question. It did not eliminate any possibilities. (Rule 19: Point out irrelevant factors)

14 S: VERTICALS?

15 T: Zero. Good question.

16 S: G.

17 T: Wrong. Your guess is inconsistent with the information you've been given. You must have forgotten that the right letter hasn't any horizontal lines. The letter you guessed can't be right - it has too many loose ends. (Rule 20: Point out an inconsistent prediction)

have not seen enough instances of each rule, the characterizations of the rules that exist are not likely to be in the most general form possible.

As the rules developed a general structure began to emerge. The first set of rules (Rule 1-15) teach the student to formulate general principles from specific, known cases, while the second set (Rules 16-23) teach the student to apply generaly principles that he has learned (abstracted) to unknown cases. Further, within the first set there is a structure among the three kinds of "Why" questions that ask for factors (Rules 2, 3, and 4). There is also a parallel structure between the three kinds of rules for handling unnecessary vs. insufficient factors (i.e., Rules 5, 6, and 12 parallel Rules 7, 8, and 13). Where such structure emerges, it is possible to specify rules (as was done for Rules 7 and 13) even though they have not occurred in the data.

In order to make the theory in any sense a complete theory, it is clearly unnecessary to pursue the search for greater structure through further data analysis. In particular, the lack of any structure among the rules for applying known principles to unknown cases emphasizes their tentative nature. One important possibility is that there may be one-to-one correspondence between the formulation rules (Rules 1-15) and the application rules (Rules 16-23).

In fact, Rule 1 in this sense corresponds to Rule 16; one asks about the dependent variable for a known case and the other for an unknown case. Trying to construct such a correspondence will turn up obvious omissions in the data-based theory presented here. For example, because there is a rule (Rule 19) for handling irrelevant factors among the application rules, it suggests there must be some such rule in the formulation rules, though there is none currently. Though the theory's origin is mired in inelegant data, it may yet find elegance through structure.

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Technical Report No. 1

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): PROCESSES IN ACQUIRING KNOWLEDGE

5. TYPE OF REPORT & PERIOD COVERED: Semi-annual Technical, 15 Sept 1975-30 Mar 1976

6. PERFORMING ORG. REPORT NUMBER: BBN Report No. 3231

7. AUTHOR(s): Allan Collins

8. CONTRACT OR GRANT NUMBER(s): No. N00014-76-C-0083

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Bolt Beranek and Newman Inc., 50 Moulton St., Camb., MA 02138

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61153N, RR042-04-01, NR154-379

11. CONTROLLING OFFICE NAME AND ADDRESS: Personnel and Training Research Programs, Office of Naval Research (Code 458), Arlington, VA 22217

12. REPORT DATE: January 1976

13. NUMBER OF PAGES: 57

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

To appear in R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.) Schooling and the Acquisition of Knowledge. Hillsdale, N. J. Erlbaum, 1976.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cognitive Psychology, Causality, Dialogue, Discourse Analysis, Education, Tutoring, Computer-assisted instruction, Learning, Teacning, Information Processing, Artificial Intelligence.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this paper is to develop a theory of Socratic tutoring in the form of pattern-action (or production) rules for a computer program. These pattern action rules are being programmed on a computer system for tutoring causal knowledge and reasoning.

The production rules were derived from analysis of a variety of tutorial dialogues. The analysis accounts for the specific

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teaching strategies used by the tutors in the dialogues within a content-independent formalsim.

The paper includes twenty-three production rules derived from the data analyzed, together with segments of the data showing the actual application of the rules in different tutorial dialogues. The strategies themselves teach students: (1) information about different cases, (2) the causal dependencies that underlie these cases, and (3) a variety of reasoning skills. These include such abilities as forming hypotheses, testing hypotheses, distinguishing between necessary and sufficient conditions, making uncertain predictions, determining the reliability or limitation of these predictions, and asking the right questions when there is not enough information to make a prediction.